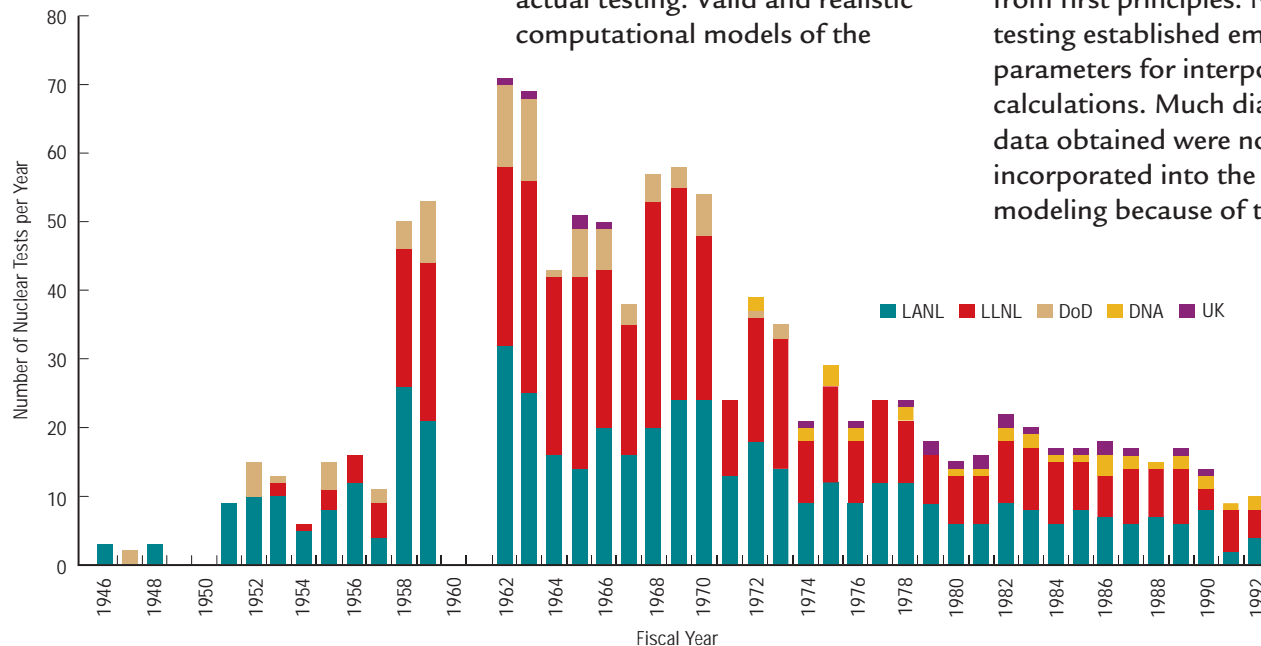


# The Reaction-History Archive

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Figure 1. This chart depicts the number and frequency of nuclear tests carried out by Los Alamos National Laboratory (LANL), Lawrence Livermore National Laboratory (LLNL), the Department of Defense (DoD), the Defense Nuclear Agency (DNA), and the United Kingdom (UK—actually their Atomic Weapons Establishment [AWE]) from post World War II until the cessation of testing in 1992.



## Introduction

The last Physics Division Progress Report on the archiving of data from nuclear tests began with the following statements, which are still true:

Los Alamos National Laboratory (LANL) has been traditionally responsible for the certification of our nuclear stockpile. With the cessation of nuclear testing, this task has become much more difficult. The charge of Science Based Stockpile Stewardship (SBSS) requires the certification of how the weapons perform as they age without the benefit of actual testing. Valid and realistic computational models of the

performance of nuclear devices are required before any confidence can be gained in calculating the effects of aging on weapons.

Over the last few decades, during testing, the approach to nuclear-weapons design was largely empirical. Nuclear testing at the Nevada Test Site (NTS) allowed for the refinement and efficiency of nuclear devices, the performance of which is very complex. Codes and physical models were not adequate for calculating device performance from first principles. Nuclear testing established empirical parameters for interpolative calculations. Much diagnostic data obtained were not incorporated into the physical modeling because of the

inadequacies of the computational tools. Presently, more powerful computers and more sophisticated models are available, but the codes must be compared to the experiment before they can be used to calculate effects of aging or design modifications of the nuclear stockpile as mandated by SBSS.

This Progress Report research highlight will discuss the definition and analysis of the reaction-history diagnostic and how it is used as a tool in SBSS. Because of the ban on actually testing a device, the next best proof that a needed change in a stockpile system will not affect yield is to calculate the weapon's effects and match the NTS test data before the change then calculate the weapon's effects after the change and see if it still matches the past NTS test data. If it does not match the data, then further study is needed to determine the effect of the change on the yield and whether the yield is changed enough to invalidate the stockpiled weapon. Without an actual testing program, certification of a weapon system after a change may be difficult.

## Why is the Archiving Program Important?

Nuclear testing was halted in September of 1992. In the absence of nuclear testing, Presidential Directive 15 states that national laboratories will have the responsibility to maintain the ability to perform nuclear tests when needed. However the directive does not detail the type of experiments and diagnostics that may be required for the resumption of testing. An indefinite testing moratorium under the Comprehensive Test Ban Treaty will inevitably lead to the loss of the capability of promptly fielding diagnostic experiments. As the hardware ages, we will be required to reconstitute experiments from the ground up. In order to meet the presidential mandated 2–3 year time period for fielding prompt diagnostics, the following areas have to be evaluated for solutions.

- The knowledge base is disappearing.
- The shelf life of appropriate hardware is depleting in a stagnant inventory.
- The ability to understand, maintain, and operate appropriate software is dependent on contemporary computer systems.

- How will 1992 recording methods keep pace with new technologies? Only part of this required recording system can be exercised on contemporary stockpile physics experiments.
- As weapon designers develop and enhance their ability to calculate weapon performance, new diagnostic data requirements will be more stringent.
- What are the requirements for a new set of scientists and engineers to develop their own recording tools in a timely and cost effective manner?
- Can a system be developed that meets the accuracy and precision requirements needed by the weapon designers?

The United States has detonated more than 1000 nuclear bombs during its testing history. Reanalyzing and re-evaluating the data that has been produced by this testing program can find solutions for the majority of the listed issues. Using the data to transfer knowledge and placing the data in an electronic form that can be used by the weapon designer are key benefits to the current “archiving” program.

## Definition

“Reaction history” and “alpha” are terms that are often used interchangeably, but alpha is actually a part of the reaction history. The reaction history is the entire measurement of a device history including not only the alpha but also the time relationships between the different stages of the device, for example high explosive detonation, neutron initiation, and, for a two-stage device, the peak flux times for the Primary and Secondary (see Figure 1, on the previous page, for a graph of the number and frequency of nuclear tests which constitute the reaction history archive). Neutron-source levels and gamma-flux levels are also a part of the reaction-history analysis. The “alpha” is the time derivative of the logarithmic flux calculated from the device’s Primary or Secondary signal. It is a measurement of the neutron multiplication rate for each of these outputs.

In a supercritical nuclear assembly the neutron population increases exponentially with time:

$$n(t) = n_0 e^{\alpha t} . \quad (1)$$

Or if  $\alpha$  is not constant, as is the case in an explosive assembly,

$$n(t) = n_0 e^{\int \alpha(t) dt} . \quad (2)$$

The quantity  $\alpha$  characterizes the degree of criticality of the assembly. The fission neutron multiplication produces gamma rays. The primary method for recording this reaction is by observing the leakage gamma radiation (flux), which may rise through 20 or more orders of magnitude. From Equation 2,  $\alpha$  is the derivative of the natural logarithm of the gamma-flux output from the device. The neutron population is directly proportional to the surface gamma output of the device. This is important because the neutron multiplication can be determined by measuring the gamma output, thus avoiding the energy time-of-flight smear of the neutron output.

## The Reaction-History Experiment

High Explosive Transit Time (HETT) is the interval between the time of the initiation of the high explosive and the time of an inflection on the alpha curve. For reaction history, this basic experimental time between the voltage breakout of the electrical X-unit that initiates the detonators on the device and the Primary alpha curve, usually alpha boost is an essential initial condition for the weapon designer. Before 1977 the HETT was measured using four oscilloscopes. After 1977, only one digitizer unit, called a biomation unit, was necessary to measure this time. About 1982, the time interval meter (TIM) was introduced to timing technology and was used to record the HETT. (A TIM is like a stopwatch that gets its start from the X-unit and multiple stops from voltage levels on various detectors, which record the current for the related alpha function. The accuracy using the TIM is a magnitude better than the  $\pm 30$  ns from oscilloscopes).

The Zipper is a pulsed 14 MeV neutron source used to initiate the fission reaction chain in nuclear devices. The Zipper is triggered at a prescribed time after the high



Figure 2. An array of oscilloscopes are needed to record the dynamic range of the device output.

explosive initiation to ensure the initiation of the fission reaction chain. The quantity of neutrons being output by the Zipper is another important “initial condition” experimental result needed by the designer. In the 1960s and the early 1970s, the Zipper output was reported in R/s. After that date it was reported in  $\text{N}/\text{cm}^2/\mu\text{s}$ . When we reanalyze one of the “older” past events, we recalculate the R/s output level to  $\text{N}/\text{cm}^2/\mu\text{s}$  and place the Zipper function in electronic output (x,y

pairs) for use by the weapon designer. (Occasionally, the designers would request the center time of the Zippers, which is extracted from the same timing system that is used to determine HETT.)

The part of the reaction-history experiment that measures the criticality, thus the overall nuclear performance of a device is the alpha curve. The dynamic range of the device output requires the use of a series of electrical instruments

to measure the total output of the device. If a perfect recording system could be designed, the measurement result would be a continuous function as previously defined by Equation 2. The inability to precisely calibrate all the recording-system components both in time and amplitude produces a result that is not continuous in gamma flux. However the derivative of the natural logarithm ( $\ln$ ) of the flux is continuous and is used to precisely relate the piecewise recording of the curve by the detector, oscilloscopes and their related electrical components.

The diagnostic measurement of the HETT and Zipper output plus the reconstruction of the device’s gamma-flux output and its related alpha function requires the expertise of a multitasking technical team. The effort actually begins with the weapon-design physicist(s) communicating with the diagnostic physicist(s) about the purpose of the test. The communication will include the expected experimental time relationships and the general shape of the output function(s). Experimentalists record the gamma-output signals of the



Primary and Secondary stages in a similar fashion, so the diagnostic challenges, which include proper selection of recording components, calibrations, and analysis techniques, are much the same for each function. Briefly describing the recording of the Primary part of the experiment is sufficient for demonstrating the complexity of the entire reaction-history experiment, which also includes the length of the time intervals between each stage's activation.

The gamma signal from the Primary covers such a large range that no one single recording device can record the entire function.

Detectors that convert the gamma flux to an electrical signal are engineered to detect the output signal at various sensitivity levels. Typical detectors used for the experiment are a suite of very sensitive photomultipliers, less sensitive photodiodes, and the least sensitive Compton diodes. All of these detectors are sensitivity-calibrated using the radiation sources in the diagnostic community, such as the cobalt source in Las Vegas Nevada and the Linac accelerator in Santa Barbara, California. Bandwidth

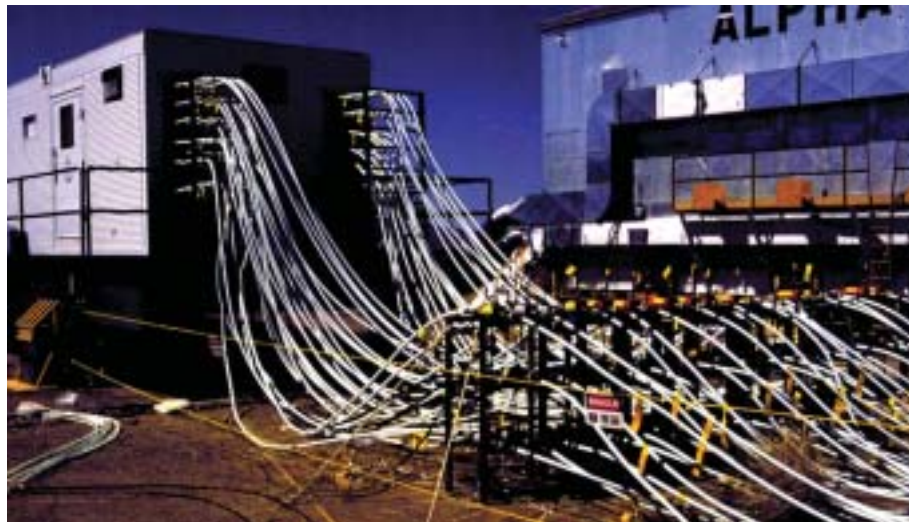


Figure3. Many cables are needed to record the range of the signal in a reaction-history experiment.

determination is also a part of the calibration of a detector. A continuous alpha curve can be constructed only if the bandwidths of the detector array are nearly equal for all of the detector recording systems. Knowledge of the detector sensitivity is the first step used by the diagnostic physicist to place detectors in the correct amplitude position to record all of the gamma-flux signal. The coverage is adjusted using distance from the device (slant range), collimator attenuation effects and slab attenuation (lead, iron, aluminum, etc.) in the

downhole rack line of the site pipe. Shielding is an important technique that eliminates cross talk between the arrays of detector recording systems. Knowledge of the effects of this “detector geometry” has to be known to determine the optimal recording of the entire gamma-flux output. The amplitude calibration of the recording system is used in the analysis of the output signal.

Because calibration uncertainties of as much as a factor of two can exist between detectors, to correctly time one detector to another, experimentalists measured transit

times from the device through the detector. This is part of a “common timing” scheme that also includes transit time through the coaxial cables to the recording station.

The measured signal paths in the recording station carry the device output to an array of oscilloscopes. Multiple oscilloscopes of various sensitivities have to be used to cover the dynamic range of a single detector. No one oscilloscope will cover the entire range of any detector. So, just as in the case of the detector array, the diagnostic physicist has to determine an optimal array of oscilloscopes to cover the sensitivity range of each detector. For some experiments, over 100 oscilloscopes were used. Using the knowledge of the basic voltage sensitivity of each oscilloscope, and applying electrical splitters, attenuators, terminators, etc., achieves the optimal amplitude coverage. All of these oscilloscopes have to be calibrated; first to determine their correct placement in the total coverage of the detector signal, and then to analyze the output signal from the device after the device has been tested.

The time-base selection and calibration for each of the oscilloscopes is another challenging part of the diagnostic set up and analysis of the curve. The Rossi display is used to record the gamma flux, which in turn is used to calculate the related alpha curve. The Rossi technique for recording a signal is basically a sine wave from an oscillator mixed with a linear signal. The frequency is related in time as:  $\text{period} = 1/\text{frequency}$ . The period is one cycle on the sine wave. This makes the time base inherently a part of the recorded signal and provides the accuracy needed to calculate the time derivative of the  $\ln$  of the flux, which is alpha. In regards to satisfying sampling theory, the selected frequency of the sine wave is dependent on the speed of the signal that the oscilloscope will be recording. For this reason it is critical that the diagnostic physicist know the general shape of the output signal from the device. On the same level as signal-path bandwidth matching, selection of the optimal Rossi oscillator frequency is necessary for the efficient recording of the output signal throughout the various changes in the shape inherent in the

output signal. The effect of inadequate sampling of the output is just as destructive to the accurate determination of the output of the device as is inadequate bandwidth or the mixing of bandwidths from detector to detector or oscilloscope to oscilloscope. In the latter days of testing, technology was advancing enough to allow serious consideration for recording the curve with high-speed digitizers and optical recording systems. The unique challenges related to the diagnostic set up of these types of systems will not be discussed in this document. The oscilloscopes that recorded the Primary gamma-flux output are reconstructed in time and amplitude with continuity confirmed by using the calculated alpha and/or the time differences of the signal paths from detector to detector.

At the time of many of the actual NTS tests, secondary-weapon designers occasionally requested that only the time between the two stage's activation be recorded because the computing hardware and software did not exist to provide the ability to calculate the device output and match it to the recorded data. The time between Primary-stage and Secondary-stage

activation is measured using a variety of diagnostic timing methods. Some of these timing systems are very complicated and careful calibration was absolutely necessary. Requests for only the time between stages are very rare during the reanalysis of the archived data because the weapon designer now has computing tools available to intelligently use all of the data from a test. This brings to light a couple of benefits of the archiving program: to extract new information and/or re-evaluate the interpretation of previously reported data. A recent reanalysis of a 1970s NTS test provided all of the data from a secondary signal and played a significant role in the certification of one of our principal weapon systems.

It was sometimes important to measure accurate gamma-flux amplitudes for each of the device's stages. The major component to accuracy is the precise calibration of the effect of rack geometry on the gamma signal. The "absolute" gamma measurement was only a diagnostic goal in the last five years or so of testing. During one of the last tests, careful attention to downhole effects on the detector

signals resulted in a flux curve with level shift errors of  $\pm 10\%$ . As stated earlier, a factor of two or three between detectors was common or at least not unusual.

Finally, there cannot be enough emphasis on the fact that the fielding and analysis of a nuclear test required the expertise of several individuals working together. For example there were teams of people covering areas that supported detector calibration and installation, cables and compensators, recording station set up, preshot analysis, standards and calibration, photo, post-shot analysis and many other tasks too numerous to mention. It was very important to document all activities accurately. Because this documentation of these activities was done, the reanalysis of past NTS events is possible.

## Alpha Analysis Tools

The basic tools for reaction-history analysis include the computing hardware and software plus the experience of the analyst(s). The ability to archive/store data electronically was not a convenient option until 1979 because of the lack of computing tools and large memory units. So, the reanalysis of events fired before 1979 starts as if the event were just executed. That is, we start by reading the oscilloscope traces, then use the event calibration documentation to run the data through contemporary software. We re-evaluate events fired after 1979 using the files that have been archived on the VAX computer. All data, reanalyzed and/or re-evaluated, is placed on the XWARP database (X-Division Archiving and Retrieval Project) for use by the weapon designers.

Before the routine use of electronic computers, the alpha data was analyzed using a slide rule and/or calculator. The resulting points were plotted on graph paper. In the mid 1960s, electronic computers were introduced, and over the years the analysis team had access to bigger and faster computers as

technology advanced. The first alpha-analysis software was written in 1964. This “batch”-operated code remained the basic tool until an interactive version was written in 1979. The 1979 version was written for the DEC operating system, and, although the hardware was updated and enhanced from a DEC PDP/1170 computer with 32K of memory to the MicroVAX 4000, the software remained unchanged through the end of testing in 1992. Because of the limited number of experienced personnel and the high level of effort needed for fielding experiments, moving to each new VAX machine required that production codes be able to be moved straight across to the new system thus avoiding a large software-conversion task. In 1998, six years after the last NTS event was fired, the software was still basically the same as it was in 1979. In 1998 it was clear that a new code was needed; one based on contemporary computing tools because the vendor was no longer supporting the VAX/VMS operating system.

The basic requirements of a new code were the ability to continue to process reaction-history data from past events, maintain the historical precision of the analysis process, and have the ability to operate independent of any hardware platform. Contemporary software was written and is able to meet these requirements now being utilized to reanalyze past NTS events. It is important to understand that the collection of

new data from NTS is not very probable, so the 50-year-old treasure (31 years of underground tests [UGTs]) must be preserved, and in addition, the “capability of reanalyzing” event data is part of that treasure. The code conversion also preserves the ability to support any “new” testing program that may be a part of the future of nuclear-weapon stewardship.



Figure4. Readyng a rail for insertion down hole.

## The Analysis of Alpha

The basic methods for analyzing reaction-history data have not changed since the first nuclear test. The philosophy is still the same, but the process has improved as technology has advanced over the years. Constructing a continuous alpha curve requires many steps starting with digitizing the film trace recorded by each oscilloscope, through amplitude fitting and baseline correcting within a detector, common timing between detectors, and general editing. When the final curve is constructed, other steps complete the analysis of the curve, such as a polynomial fit, deconvolution, a continuous-flux curve, timing between the two stages, and analysis of the front-end data, which includes the neutron-initiation analysis and high-explosive detonator analysis.

To determine continuous alpha, the function used for device performance, a primary curve may need the relationship in time and amplitude of up to 10 detectors covered by 60–120 oscilloscopes to record the large dynamic range produced by the device. During the analysis of the reaction history, the recording system for each

oscilloscope has to be taken into account, that is, the downhole geometry, cable lengths, and recording-station configuration. A further complication is the need for higher bandwidths to reduce data distortion as alpha increases. Some early NTS data (1965–1980) may have been recorded using up to four different bandwidths, which encourages less distortion for the faster regions of the curve—but makes it nearly impossible to construct a continuous curve. Data recorded at different bandwidths cannot be composited as one curve without precise timing between systems or by numerically applying a deconvolution process. Even then, data precision is compromised.

Obtaining a continuous alpha curve is one goal of our analysis. Of equal importance to the weapon designer is the distortion effect of bandwidth on the entire set of experimental data because the data produced by the theoretical calculation has to be folded with the response of the experimental-data recording system to legitimately match the calculation to the experimental data. The

required precision of this match is presently a collaborative study between P, X, C, and DX Divisions. The results of the study promise to have a significant impact on the accelerated strategic computing initiative (ASCI). The ASCI program is fundamentally a method of testing weapons on supercomputers—hopefully satisfying the requirements of an actual testing program.

The recording system includes the detector, the coaxial cable system, and the various signal paths in the recording station. Over the years the system response was measured very carefully by inserting a step function into the system and recording the distortion of the output step function. This measured response is always given to the designer as part of the complete set of data for an event that is placed on XWARP.

Using the contemporary software that went into production in late 1999, many examples related to the speed and efficiency of the new software plus the large memory of the PC show the improvement in the analysis process. It is important

to realize that through all the software changes the precision of the curve has remained constant over all the years of the UGT data interpretation. This precision has been verified over and over again during the reanalysis of past events during the past eight years.

Presently, the designers have become very aware of the cache of data on the XWARP database and have been asking for detailed interpretation as they learn what is available to them for each set of reaction-history data. In examining the database, they find system information starting from the device and ending at the recording oscilloscope. This includes all the downhole parameters and the system response needed to fold with their calculation. Several ASCII-format files provide the final gamma-flux, alpha, and neutron-source curves. Also included in the database are scanned analysis reports for all the UGTs executed by LANL. Some Lawrence Livermore National Laboratory (LLNL) data is also on XWARP. It is hoped that Aldermaston Weapons Establishment (AWE-United Kingdom) test data will soon be on the database.



## Results of the Archiving Program

Reaction history, which has been the basic measurement of device performance on virtually all nuclear tests, is only one of many experiments that are being archived for use by future scientists. Using reaction history as an example, a list of benefits from the archiving program are as follows.

- The knowledge base is being transferred. New physicists and analysts are being integrated into the program. An important feature is our effort to focus on communication between the experimentalist and the weapon designer.
- P-22 is placing the reanalyzed reaction-history data in a well-organized electronic database for convenient access by the nuclear-weapons community. Electronic archiving is more permanent and useful than hard copy archiving.
- Computer software is being transferred and/or developed for contemporary computing requirements. It is important that this area be continually updated because of the rapid changes that occur in computer technology.
- Reanalyzing a set of data requires the understanding of the recording system. This understanding can be applied to any new hardware that may have to be fielded again—whether it is in its original form or in a similar reconstituted system based on modern technology.
- Reanalyzing the data has, in many cases, led to a better understanding of the data and has motivated the investigation of new areas of study which enhances the value of the data. An important fact to remember is it is very unlikely that the U.S. will collect new nuclear test data for some time to come.
- A suite of contemporary experiments can be done, and the knowledge gained from past NTS data is a precursor to deciding which of these experiments have the most benefit to the certification of the stockpile and the understanding of the weapon codes being used by the weapon designers.

## State of the Reaction-History Archive

The reanalysis of archived reaction-history data from NTS has been funded since 1993. The annual funding has grown from \$100,000 in FY93 to \$1,523,000 in FY01. The FY01 amount covers all or part of six regular full-time employees (FTEs) in P-22. In addition, this budget also funds five subcontractors. Additional help for the archiving program (about two FTEs) is obtained from our Bechtel contractor.

P-22 has data in its hard copy archive for all of LANL's 408 UGTs. Of these 408 tests, the vast majority are either directly related to the current stockpile or have significant physics value to the nuclear-weapons program. By the end of FY01, all tests directly related to the stockpile will be in electronic format and stored on the XWARP database for use by the weapon designers. Up to five years of effort will be needed to complete processing of the other events.

P-22 has expended a significant effort to train and mentor individuals to continue our communication with the designers in X-Division after some of our key personnel retire in FY01. This is

particularly important with regard to the communication with the recently formed Campaign committees. Additional help, primarily with basic reanalysis problems, is being recruited from the P-22 subcontractor, Bechtel Corp. Bechtel has been particularly helpful with the required software conversion from the VAX/VMS system to the Windows NT computing platform. The last major production code will be completed in FY01.

All data and software from the VAX computer are being transferred to PC servers and the VAX will be decommissioned. The principle production codes are on the server and in production. Other significant production codes that deal with recording-system design and evaluation, calculation of downhole effects, and the convolution effect on data by recording systems are in various levels of software conversion.



Increasingly, the weapon designers are requiring detailed interpretation of the available reaction-history data. This includes verifying the accuracy and completeness of stored data and in many cases comparing the data from one test to another. As the ASCI project develops over the next few years, an intense interest in the advanced diagnostics archived by P-22 promises to develop. Presently, these advanced diagnostics, such as various radiation-flow experiments, spectrometry, and other energy measurements are archived in hard copy form and accounted for in a P-22 database.

## Summary and Outlook

### *Project Description*

The P-22 archiving project emphasis is on the conversion of reaction-history data from NTS events to an electronic format that is readily available to the weapon's community and can be understood by the weapon designer. The data are used to enhance the understanding of the performance of a weapon system and are used in the development of weapon design codes. The comparison of the data to theoretical calculations is a primary exercise used in SBSS to certify the current stockpile's safety and reliability.

In addition to reaction-history data analysis, P-22 owns and has in part analyzed data from advanced diagnostic experiments including electromagnetic pulse (EMP). The archiving of fielding issues surrounding the EMP experiment plus the interpretation of the data is presently key information for the Threat Reduction Program. Writing diagnostic procedure handbooks, analysis reports, and the conversion of production codes to a contemporary platform are an integral part of the P-22 archiving program. Finally, mentoring to preserve the knowledge gained from 50 years of nuclear-weapon testing is a requirement of the P-22 archiving program.

### *Collaboration and Coordination*

The P-22 archiving program closely collaborates with the weapon designers to insure the availability of data on a priority basis. Much effort is expended to insure that the designers fully understand the interpretation of the data available to them. With regard to the actual analysis task, Bechtel, a Laboratory contractor, is called upon to perform initial analysis of reaction-history data, which includes in part, film reading, recording system calibration input, and data compositing.

A study of the quality of the alpha function is presently in progress, using expertise from TSA-1 and DX-3 as well as P-22. The Laboratory is mentoring interested individuals that will potentially replace current archiving team members who are nearing retirement. Finally P-22 is an important partner in the LANL NWAP (Nuclear Weapon Archiving Project).

### *Issues, Constraints, and Assumptions*

The most important issue in the P-22 archiving program is "aging team members and no definite replacements". The Bechtel contractor has added a new FTE to the effort and training by P-22 personnel is in progress. Two TSMs in P-22 have shown some interest in the archiving program and have volunteered to begin a training plan. The lack of personnel contributes to our inability to keep past skills alive—a real readiness issue. The recent LANL hiring freeze has been a very real roadblock to the future health of the P-22 archiving program. On a positive note, there is some indication that the program will have sound funding for the foreseeable future.

## Further Reading

Written materials related to reaction history can be found in the P-22 vault. Many of the papers are unclassified. Contact Kent Croasdell [(505) 667-2483, [croasdell@lanl.gov](mailto:croasdell@lanl.gov)] for further information or a copy of an unclassified report.

### *Unclassified Reports*

E. Bennett, “Fifty Years of Reaction History,” Los Alamos National Laboratory report LA-UR-92-2667 (August 1992).

E. K. Hodson, “Predictable Unfolding in the Time Domain,” Los Alamos Scientific Laboratory report LA-03830 (December 1967).

E. K. Hodson, D. R. Thayer, C. Franklin, “Adaptive Gaussian Filtering and Local Frequency Estimates using Local Curvature Analysis,” Los Alamos National Laboratory report LA-UR-80-0481 (February 1980).

### *Classified Reports*

E. K. Hodson and K. C. Croasdell, “Recording Reaction History with Digital Systems (U),” Los Alamos National Laboratory report LA-CP-93-0302 (November 1993).